FINAL REPORT

Title: Multi-Scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions

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Abstract

Spot fires caused by lofted embers (i.e., firebrands) can be a significant factor in the spread of wildland fires. Embers can be especially dangerous near the wildland urban interface (WUI) because of the potential for the fire to be spread near or among structures. Many studies have investigated the transport of lofted embers and the subsequent ignition of material on the ground, but knowledge regarding which fuel and environmental conditions control generation rates is sparse. Such information is needed to help inform ember transport models and to assess risks of ember generation for different fuel and environmental conditions. This work seeks to identify ember generation characteristics for different fuel characteristics and environmental conditions at multiple length scales. In laboratory experiments, dowels and natural samples of approximately 125 mm long were burned in a vertical wind tunnel. The species, moisture content, diameter, crossflow temperature, and crossflow velocity were varied. A factorial study with the time to generate an ember as the dependent variable found that diameter had the largest effect on the time required, followed by species. A subset of the data from the factorial study was used to compare manufactured dowels to natural samples. It was observed that natural samples of Douglas-fir took roughly 55% longer to generate an ember than corresponding manufactured dowel samples. At a larger scale, trees 2.1-4.7 m tall were burned in outdoor, semi-controlled conditions. Generated embers were collected in trays filled with water and on fire resistant fabric. The fire resistant fabric gives an indication of ember temperature upon deposition because only "hot" embers char the fabric. It was found that both the number of embers and char marks are significantly dependent on the fuel species. Of the species tested (Douglas-fir, grand fir, ponderosa pine, and western juniper), Douglas-fir generated the most embers per kilogram of mass loss during testing. Grand fir and western juniper generated the most char marks per kilogram of mass loss. It was observed that western juniper had the largest percentage of "hot" embers, with roughly 60% of the embers being hot enough to leave char marks. A technique was developed to identify important environmental factors that influence spotting distance at the forest-scale. This was accomplished by analyzing infrared images collected by the National Infrared Operations Program. Wind speed had the greatest influence on the propagation distance of embers. The comparisons of the observed maximum spotting distances with the predictions from Albini's [1] model showed that modeled results were typically under predicted.

1. Overview and Objectives

Spotting is a significant mechanism for wildland fire propagation. During this process embers are produced, lofted in the fire plume, transported past the flaming front, deposited, and, if sufficiently hot, can ignite the fuel beyond the actual fire front [3–6]. This method of flame spread is particularly significant for intense fires and at the wildland-urban interface (WUI) [3,7]. At the latter location, embers which penetrate or lodge on homes can lead to ignition [8]. Ember production data from vegetative fuels has rarely been studied and understanding the role of embers in the WUI is not well understood, despite its significance[3,9]. Ironically, many fire models depend on ember production as an input. Consequently, the predictive capability of the models is limited. In summary, there is a critical need to understand ember production, entrainment, transport, and ignition as a function of vegetation condition and burning intensity and environment to strengthen fire management and predictions, develop safety policies, and optimize resource usage.

Measurements of ember transport and production rates have been hindered by multiple challenges. First, they are difficult to directly measure. Moreover, production and transport rates depend on multiple factors such as the type of vegetation, shape of the vegetation, moisture content, and wind speed. The limited studies of embers in wildland conditions have typically measured ember size distributions for a small number of fuel or environmental conditions [9–11]. While valuable, this data is not adequate to determine production rates, nor does it determine which vegetation and environmental factors control production. A second challenge is that ember production and transport should be determined at forest-scales. However, the extensive resources required for testing and the broad range of environmental conditions limits the amount of testing which can be performed. An approach is needed to correlate small-scale ember generation and transport testing to forest-scale results.

With this background and motivation, the <u>overall goal</u> of the project was to directly measure generation rates and transport distances for multiple fuels (vegetation and structural) and environmental conditions. It was <u>hypothesized</u> that ember production rates, transport, and sizes are primarily controlled by a few parameters (e.g. fuel/vegetation type, ambient wind speed, and fire intensity) and that results obtained at large-scales are correlated to results collected at small-scales.

The <u>specific tasks</u> proposed to satisfy the overall goal and evaluate the hypothesis are listed below.

1) Measure the size of embers and rate of production for different fuels and environmental conditions.
2) Determine the environmental and fuel conditions which control ember production.
3) Quantify ember temperatures at and downstream of the source of generation.
4) Establish a methodology bridging data and correlations from small-scales to forest-scales.
5) Correlate ember size, shape and density to transport distance, deposition rate and ember deposition temperature.
6) Establish a link between ember sizes, shape, and density to the inherent capacity to ignite fuels. An additional task was proposed to transition results to fire management decision makers.
7) Integrate experimental findings and algorithm into a computational tool (WindNinja).

Tasks 1,2, 5 and 6 and modified versions of Tasks 3 and 4 were accomplished, as described in the Results and Discussion Section. Task 3 was modified to focus on quantifying the number of embers that were deposited on the ground and were hot enough to char pieces of fabric treated with fire retardant. While this approach does not provide specific temperature values, it does quantify the number of embers that are hot upon deposition. The focus of Task 4 was shifted to establishing a methodology for evaluating ember generation at tree-scales. Challenges in collecting data of ember generation characteristics during prescribed burns limited the ability to bridge the method to forest-scales. It was determined that more work is needed prior to development of a new ember production and transport model; part of the needed work includes assessment of the current spotting algorithms embedded within existing operational tools to determine their appropriateness as well as their deficiencies. Consequently, Task 7 was shifted to focus on analysis of spotting at forest-scales and evaluation of the widely-used Albini spot fire model [2] currently incorporated into operational wildland fire modeling tools (e.g., FlamMap, FARSITE).

2. Background

Climate change and fire exclusion are the likely causes of significant increases in acres burned and overall intensity of wildland fires, which has resulted in increased risk to human safety and property in the WUI [12–14]. Spotting is a significant wildland fire spread mechanism and a threat to structures in the WUI. Spotting is the process by which burning embers (also known as firebrands) are generated at the fire front and are transported by the wind away from the fire front. A spot fire can then initiate if the embers land on flammable material, such as a house or biomass [15]. Embers can travel large distances, for some conditions on the order of kilometers [16]. Lofted embers can be particularly challenging when protecting WUI areas because they can be transported past barriers (e.g., rivers).

The ability to predict the threat of spot fires is limited because of gaps in understanding about the physical and chemical processes that control ember generation, transport, and ignition. Thus, there is a need to better understand these processes to allow fire professionals to better assess threats associated with spot fires. Transport and ignition have received the most attention, while relatively few studies have considered the processes that control generation of embers. Arguably, generation of embers is the least understood aspect of the spot fire process. This study focuses on identifying the importance of several key physical and chemical parameters that control ember generation, such as fuel species, fuel diameter, fuel moisture content, crossflow temperature, and crossflow velocity.

Numerical models of burning wooden cylinders have been used to better understand the ember generation process. Barr and Ezekoye [17] predicted breakage (i.e. ember generation) using a fractal tree model coupled with a thermal decomposition model. Breakage occurred when the strength of the cylinder degraded (due to decreased diameter because of oxidation) to less than the drag-induced stress. By coupling this model with a transport model, they found that an optimal branch diameter (i.e., roughly 4 cm) for generating embers that can form spot fires. The branches need to have a diameter that can break during a typical fire residence time, but large enough to not be consumed during transport. The critical diameter is significantly larger than the diameter of most samples collected during experiments (described later). The discrepancy between the critical diameter and those measured was attributed to differences in physical properties of dowels and natural samples; natural samples tend to have more defects, have a nonuniform shape, and are coated in bark [17].

The diameter and density of the fuel are parameters that can influence ember generation. For example, Caton [18] found a linear relationship between dowel density and flexural strength after exposure to various heating conditions. This correlation varies between species which suggests that fuel species may influence ember generation physics because of different strength characteristics (in addition to having different densities). Based on this analysis, it was reported that dowels with a diameter of 6.35 mm or less would break when exposed to typical wildland fire conditions.

Laboratory and field studies have reported the size distributions of embers for several different tree sizes, moisture contents, and species. This information provides insights into the ember generation process. Several field studies reported that embers collected during prescribed and wildland fires generally had a projected cross-sectional area less than 2 cm^2 [19–22]. Manzello et al. [10], [23] collected embers generated from burning single Douglas-fir and Korean pine trees. Trees with a larger crown height produced larger embers (4 mm average diameter) than trees with a smaller crown height (3 mm average diameter) for similar wind speeds and moisture contents. The difference in average ember size for the different tree heights shows that tree height influences ember generation. It is worth noting that the heat release and tree morphology varied between tests as the tree height (i.e., quantity of fuel) was changed. This is important because the larger average ember size may be influenced by heat release and/or tree morphology (i.e., crown height, fuel loading, and size of branches). It was noted that trees with a moisture content greater than 70% did not sustain burning. This observation suggests that, at least at the extremes, moisture content may be an important parameter controlling ember generation.

The size distribution of embers provides insights into the characteristics of the branches and material that generate embers. Size and mass distributions of embers for a variety of tree sizes, species, and moisture contents have been reported in laboratory and field studies. As an example of such studies, El Houssami et al. and Filkov et al. [20,21] collected embers in trays filled with water during controlled burns at the Pinelands National Reserve. Approximately 73% of the collected embers were bark, while the rest were comprised of branches. Approximately 80% of the total firebrands had a cross sectional area less than 2 cm^2 [21]. The diameters of the cylindrical firebrands were generally between 1 and 6 mm [20]. The work just referenced, as well the results summarized in other literature, show that the projected area of most embers collected during wildland fires is less than 2 cm^2.

Fire behavior can influence ember generation characteristics, including the number of embers deposited within a region (i.e., ember flux). Thomas et al. [22] conducted an ember collection study in 2016 using cameras to record the initial time, duration, and final time at which firebrands were deposited into pans filled with water during a controlled burn. Fire behavior was monitored at the same time in order to establish a correlation between fire behavior and instantaneous ember flux at a known distance downwind of the fire. They found that there was an almost direct correlation between ember flux and upwind fire intensity. Generally, a higher upwind fire intensity lead to a higher ember flux.

Identifying the "hot" embers is important to more fully assess risks of spot fires. The average projected area of "hot" embers (based on char marks left on fire resistant fabric) was measured during a series of controlled burns for the Canadian Boreal Community FireSmart Project [24]. It was observed that about 90% of the char marks on the fabric were less than 0.1 cm^2. In similar attempts to quantify "hot" embers, the size and number of holes melted through trampolines near areas with recent wildland fires have been quantified [19], [25]. In one such study, nearly 1800 holes were measured, with 85% of them having an area less than 0.5 cm^2 [19]. Embers that formed these holes were likely from a forest comprised of white fir and Jeffrey pine. In another study, 90% of the holes measured were less than 0.5 cm^2 [25]. The embers that formed these holes were likely from a forest comprised of loblolly pine and yaupon. What is not fully understood from these studies is how the total number of embers that are generated (e.g., those collected in water pans) compares to those that are hot enough to ignite a fuel bed.

The crown height and moisture content of trees influences the characteristics of ember generation. Manzello et al. [10,23] burned Douglas-fir and Korean pine trees in quiescent conditions, collected the embers, and characterized the ember size distribution. Douglas-fir trees with a 2.4 m crown height produced embers with an average diameter of 3 mm, while 4.5 m crown height trees produced embers with an average diameter of 4 mm. Trees with a moisture content higher than 70% were unable to be torched without additional heat input. It should be noted that changing crown height also changes the heat release and tree morphology (i.e., fuel loading). The size of embers collected during this work are in the same size range as embers collected during wildland fires [20–22]. This suggests that tree-scale studies may accurately capture physics present in a wildland fire. At smaller scales, the diameter and density of branches and the burning conditions influence generation characteristics. Caton [18] explored the effect of various heating conditions on strength properties for several types of wooden dowels. She found that the diameter and density are key parameters that control the type of failure for each sample, but combustion characteristics (e.g., heated with hot plate vs. propane flame) also influence generation. A linear relationship between dowel density and flexural strength was observed whose slope varied for different species. The fracture strength data was used to calculate a wind-induced drag force required to fracture the sample by using a simple mechanical breakage model [26]. It was predicted that dowels with a diameter of 6.35 mm (smallest diameter tested) would break when exposed to typical wildfire conditions.

With this background and motivation, a series of branch-, tree- and forest-scale studies were conducted and ember generation characteristics were quantified. It is expected that this work will help to identify how well knowledge about ember generation characteristics at branch-scales can be extended to tree-scales and identify controlling physics that extend to forest-scales. Additionally, this work will help elucidate the relative propensity for several tree species to generate embers, and the size characteristics of those embers.

3. Materials and Methods

Three types of experiments were used while working to satisfy the overall goal. The first set of experiments were branch-scale studies where dowels or parts of branches were inserted into a vertical wind tunnel. The time required for the material to break and form embers was measured as the size, species, moisture content, temperature, and wind speed were systematically changed. Additional details regarding the experiments and analysis are reported in Section 4.1. The second set of experiments were tree-scale studies where groups of 1, 3, or 5 trees were positioned vertically and allowed to torch as a bed of straw was burned. The embers generated by the burning trees were collected in trays of water or on fabric treated with fire retardant. The total number and the number of hot embers were characterized and related to the specifics of the trees. The results from this study were used to better identify how tree characteristics influence the generation of embers. Additional details regarding the experimental approach and the analysis is reported in Section 4.2 The third experimental approach consisted of attending wildland fires and prescribed burns (with collaboration of The Nature Conservancy of Oregon) and collecting embers on fabric treated with fire retardant. Data collected from these campaigns were used for comparing ember generation characteristics from a forest-scale burn to those from the tree-scale burn. Section 4.3 provides additional information regarding the forest-scale experiment.

4.1 Branch-scale Studies

A vertical wind tunnel was used to evaluate the time required for ember generation for different species of trees, fuel characteristics, and environmental conditions. The wind tunnel consisted of a 150 x 250 mm duct with two propane torches (only one was operated for some conditions) and two industrial fans. This arrangement allowed the temperature and crossflow velocity to be systematically varied. A model of the wind tunnel is shown in Figure 4.1. The wood samples were placed 250 mm downstream of the torches and 950 mm downstream of the fans. One or two branches or dowel samples, oriented in the x-direction, were placed in the high temperature crossflow. Two expanded metal grates were placed between the torches and the samples to create a more uniform temperature and velocity distribution near the sample. A visual camera was used to record a video of each sample placed in the crossflow.

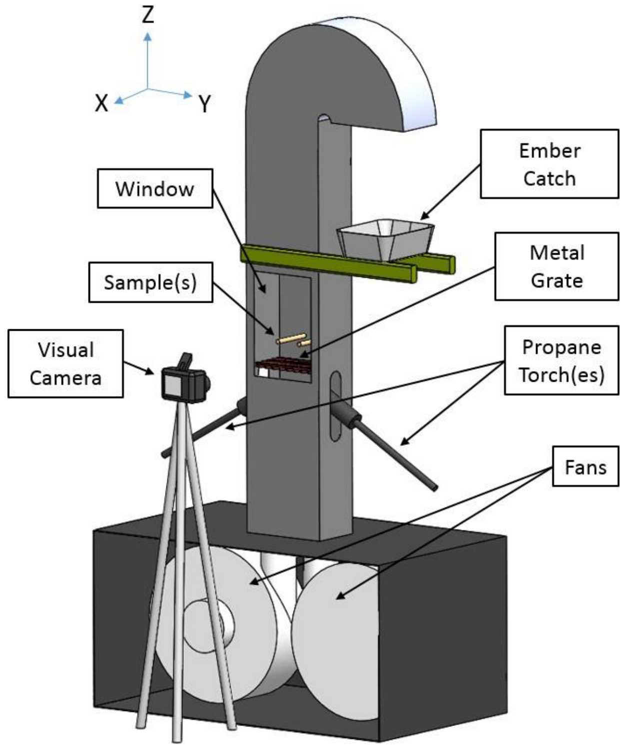


Figure 4.1 Model of the vertical wind tunnel used to evaluate ember generation characteristics.

Figure 4.2 shows the average temperature distribution that each sample experienced. This was measured by traversing a type K thermocouple across the depth of the wind tunnel, in the locations where the dowels were inserted. Both high (peak = 1200 K) and low (peak = 1000 K) temperature conditions were evaluated. The temperature ranges were selected to be representative of those that a tree might experience during a typical wildland fire [27,28]. The temperatures were controlled by metering the propane flow rate using a rotameter. Lower temperatures were observed near the walls because of cooling and the distribution of heat release from the burners. The heat release rate was between 37 and 50

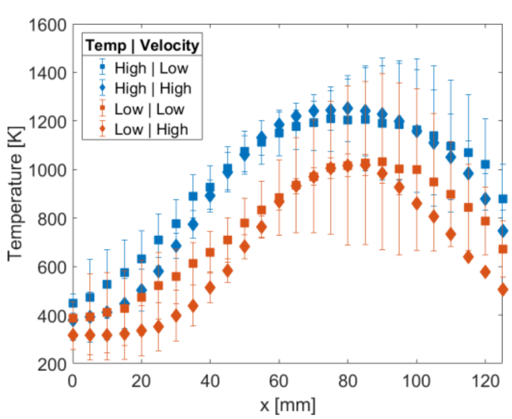


Figure 4.2 Temperature profile from base of sample (x=0) to tip of sample (x=125 mm).

kW (low and high temperature cases, respectively). By assuming simple, 1-D convective heat transfer, the heating rate of the samples can be estimated to be between 128 - 216 W for 6 mm diameter samples and between 81 - 126 W for 2 mm diameter samples. The range of heat transfer is due to the range of conditions evaluated. The grates placed downstream of the propane torches glow during testing, so radiative heat transfer from the grates to the samples was analyzed. The heat transfer rate was calculated to be approximately 8 and 3 W for the 6 and 2 mm diameter samples, respectively. This is negligible compared to the convective heat transfer.

Figure 4.3 shows the average velocity distribution along the x-axis in the location where each sample was placed. The magnitudes of the two crossflow velocities are similar to what a branch might experience during a wildland fire [29,30]. The uncertainty reported in Figures 2.2 and 2.3 are precision uncertainty (at least 4 replicates) with 95% confidence. The relatively high uncertainty in the temperature measurements at some locations resulted from limitations in how the fuel flow rate was metered and sensitivities in the distribution of the heat release to slight changes in the wind tunnel arrangement (e.g., warping of the wind tunnel walls).

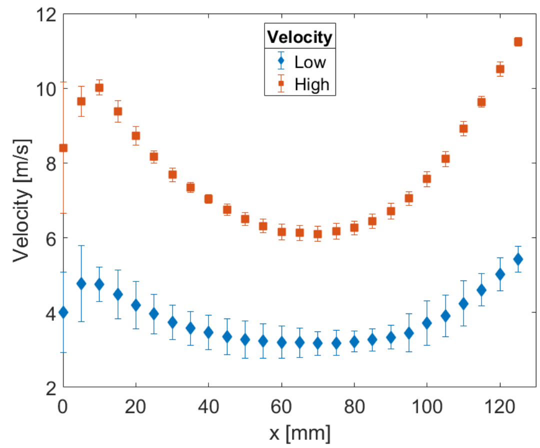


Figure 4.3 Velocity profile from base of sample (x=0) to tip of sample (x=125mm).

The physical characteristics of the samples that were varied during the experiments include: diameter (2 and 6 mm), species (Douglas-fir, western juniper, ponderosa pine, and white oak), moisture content (0.5% and 15%), and condition (dowel and natural). The objective in varying the sample conditions was to elucidate the aspects that control ember generation of branches. The nominal sample diameters were selected based on embers collected in previous studies [4,31]. All samples were 125 mm in length, resulting in aspect ratios equal to 62.5 and 20.8 for the 2 and 6 mm diameter samples, respectively. The species were chosen for their abundance in the western United States and their contrast in tree morphology and density.

The samples were dried using an oven at approximately 70 °C and weighed at periodic intervals until the mass no longer changed. By measuring the relative humidity of the room, the equilibrium moisture content of the dry dowels was determined to be roughly 0.5% [32]. The 15% moisture content samples were created by placing dried samples in a humid environment until the desired moisture content was achieved. Dowels and natural samples were investigated because they offer unique characteristics. Dowels are useful because the geometry is consistent between samples, but only partially represent physical characteristics because they have no bark and are made of heartwood. Natural samples may have inconsistent geometries, but are representative of fuels in a wildland fire. The natural samples evaluated were Douglas-fir and had average diameters of 2.05 ± 0.11 mm and 5.61 ± 0.14 mm. The average diameters of the manufactured Douglas-fir dowels had average diameters of 2.13 ± 0.06 mm and 6.14 ± 0.07 mm. Figure 4.4 shows an example of the samples used. The light-colored samples are manufactured dowels, while the darker samples are natural samples with intact bark.

Figure 4.4 Examples of Douglas-fir samples that were burned. From left to right: 6 mm diameter dowel, 6 mm diameter natural sample, 2 mm diameter dowel, 2 mm diameter natural sample.

The fuel and environmental conditions evaluated were intended to be representative of wildland fires. However, the range was not comprehensive of all conditions possible in fires because of the finite scope of the project. Nonetheless, the results from this work are expected to be applicable to more extreme conditions and provide insights in ember generation for low intensity burns. Identification of the sensitivity of ember generation characteristics to fuel and environmental conditions were made through visual observations of the time when the embers were generated and by using a design of experiments (DOE) factorial approach. The data were processed using an ANOVA in R. Each testing condition had at least three replicates. A video of each sample being burned was collected and converted into a series of images to allow for comparison between different conditions at similar times. An example ember generation from a 6 mm, oven-dried, Douglas fir dowel is shown in Figure 4.5. The sample starts burning roughly 4 seconds after being inserted into the flow. Steady combustion is observed near the center of the sample. At 24.5 seconds, the sample deflects in the direction of the crossflow before failing and yielding an ember. The time to ember generation for each sample was defined to be the time between sample insertion and when a majority of the sample was lofted. If several small embers were generated, the generation time was defined to be the average of those generation times.

Figure 4.5 Sequential images of an ember generation event. The first image was taken roughly 25 seconds after the sample was exposed to the heated crossflow. The time between each image is approximately 66 ms.

4.2 Tree-scale Studies

4.2.1 Experimental Approach

Figure 4.6 shows a schematic of the outdoor testing arrangement. The arrangement consisted of a 3.1 x 1.2 m straw bed (average straw depth of 0.42 m) with the tree(s) to be torched located at one end of the bed. The bed was oriented in such a way as to keep the tree(s) downwind during typical ambient wind conditions. An industrial fan with a diameter of 1.1 m was mounted at the upwind end with a centerline height of 2.4 m. It was intended that the fan create a known crossflow velocity and direction. However, it was observed that the crossflow created by the fan was dominated by any ambient wind. The average wind speed (across the fan diameter, centered at a height of 2.4 m) produced by the fan is as follows: 1.2 m/s at the closest row of trees, 1.0 m/s at the second row, and 0.8 m/s at the farthest tree. These measurements were collected using a Kestrel 2000 Wind Meter. A weather station was used to record the local wind speed and wind direction at 30 seconds intervals during each test. This weather station malfunctioned during some of the testing, so weather data is only available for 15 of the 36 tests. The average ambient wind speed recorded by the weather station for the 15 tests was roughly 0.59 m/s.

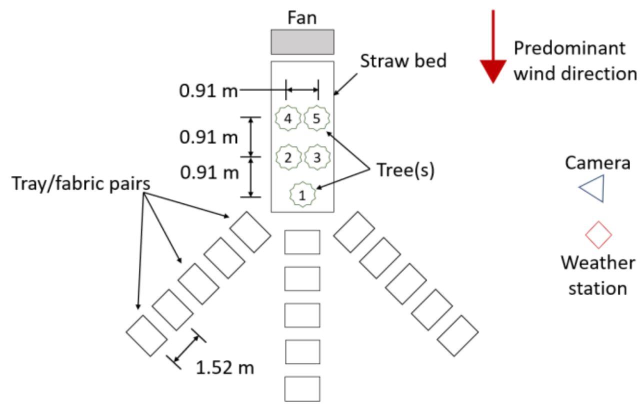


Figure 4.6 Schematic of testing arrangement.

Fire resistant fabric and aluminum trays filled with water were arranged downwind of the test section. Each small box on the schematic in Figure 4.6 indicates a fabric and tray grouped together, with approximately 1.5 m between each set and between the first row and tree #1. Each set of tray and fabric was oriented such that the tray was closer to tree #1 (labeled in Figure 3.1). The fabric pieces and trays had dimensions of approximately 0.43 x 0.40 m and 0.38 x 0.25 m, respectively. The advantage of using both fire resistant fabric and water trays is that the fabric gives information about the temperature of any embers deposited because only "hot" embers char the fabric. Embers deposited in the water trays are immediately quenched and therefore any information about temperature and energy is lost, but ember size information is captured.

Figure 4.7 Example image from an experiment. This test had five western juniper trees.

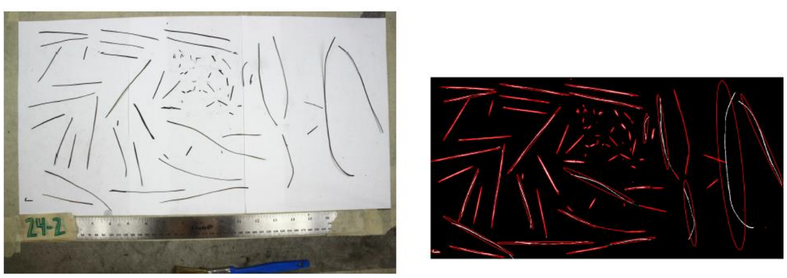
Tests were conducted with one, three, or five trees (arranged as shown in Figure 4.6) in order to vary the heat release. Three replicates of each test were performed, so a total of 108 trees were burned. The species tested were Douglas-fir, grand fir, ponderosa pine, and western juniper. These species were chosen for their potential to generate embers and their prevalence in the Pacific Northwest. The trees were harvested and allowed to dry outside for two to three months, depending on when the testing was conducted. Table A.C.1 shows the moisture content, initial mass, height, and DBH (diameter at breast height) for each tree. The average height of the trees tested was 3.7 m. Moisture content (dry basis) of the trees was measured immediately before testing by destructively sampling the trees and drying the samples in an oven at approximately 105°C until the sample weights did not change. The average moisture content at the time of testing was 21% for Douglas-fir, 29% for grand fir, 40% for western juniper, and 97% for ponderosa pine. The ponderosa pine moisture content was higher than the other species despite drying the ponderosa pine trees longer. It was decided to burn the trees even with their high moisture content because opportunities for testing outdoors were closing due to city regulations.

The straw bed was ignited on the upwind edge, and the fire was allowed to freely propagate to the tree. 20 ± 0.8 kg of straw was used for each test. An example image of a tree torching during a test is shown Figure 4.7. On average, torching required about 70 seconds. Juniper trees tended to have much larger flames than the other species.

4.2.2 Data Analysis

The size and number of embers collected in the trays during testing was determined by laying the embers out on a white background and taking a high resolution image. Each image was then cropped, converted to grayscale, and binarized using an intensity threshold function in MATLAB. The number of embers was determined by counting groups of connected pixels. The number of embers was determined by counting number of pixels per object, and converting that number of pixels to an area using the pixel resolution. The pixel length was calculated using a known distance in each image (a standard ruler). The resolution for the images of embers was 0.11 mm per pixel, and 0.13 mm per pixel for the fabric images.

Ember length was determined by modeling each object as an ellipse using a multivariate normal distribution; the major axis of each ellipse was assumed to be the ember length. The ember diameter was then determined to be the ember area divided by length (assuming each ember had a rectangular cross section). The same technique was used to process the fire resistant fabric that received char marks. Figure 4.8 shows an example of the analysis for the embers collected in one tray and Figure 4.9 shows an example of the binarization for a piece of fabric. The red ellipses overlaid on Figure 4.8(b) show the multivariate normal distribution predicted for each ember. Several embers would have a qualitatively poor fit for ember diameter if the diameter was assumed to be the minor axis of the ellipse, but recall that the ember diameter is determined by dividing the ember area by the length. This provides more reasonable diameters than if the minor axis of the ellipse was used. Another source of error for the fabric images is when char marks overlap. The analysis assumes any connected group of pixels is one char mark, even though it can be two or more overlapping marks. In order to roughly quantify the possible error in ember and char mark counts, the number of embers or char marks was manually counted for six images (three for ember and three for char marks). Generally, calculated values were within 12% of the manually counted values. The calculated ember counts tended to be slightly higher than when counted by hand, while the calculated char mark counts were slightly lower than when counted manually.



(a) (b)

Figure 4.8 Example of original image and binarized image with fit ellipses of collected embers.

For two tests with juniper trees, the tree(s) burned intensely enough to fully char pieces of fabric in the row closest to tree # 1, destroying the data about "hot" embers from five pieces of fabric. As a result, data from these locations has been removed. All mass and mass loss values reported have been corrected for moisture content. No correlations of ember generation with respect to wind conditions are described in this paper because there were not enough data to confidently report trends and dependencies. Also, the wind speeds that were recorded were relatively low (i.e.,0.59 m/s), and as a result are expected to only have secondary effects. The authors recognize that wind speed and direction may have a significant role in the generation and transport of embers. Nonetheless, it is believed that the work described in this study contributes to the community's understanding of the physics governing ember generation in wildland fires neglecting wind effects.

(a)

(b)

Figure 4.9 Example of original image and binarized image of char marks.

4.3 Forest-scale Studies

4.3.1 Study design

Daily large wildfire perimeter data collected by the National Infrared Operations Program (NIROPS) were used to (1) assess the possibility of utilizing this data to determine spotting distances and (2) evaluate a popular theoretical model developed by Albini [1] to predict the maximum spotting distance for single and group tree torching. The NIROPS program is frequently requested during large wildfires to assist fire managers in gathering and interpreting infrared (IR) data to relay consistent and reliable information on fire position [33]. A team of IR technicians, interpreters, and pilots are assembled to deploy and operate aircraft-mounted IR equipment that is suited to detect small heat sources (i.e., 15–20 cm in diameter) over vast areas in a short amount of time (40.5 $km^2 \cdot min^{-1}$) [34]. The raw data are processed by IR interpreters to produce geo-corrected products that are then transmitted to fire managers and stored on a publicly accessible FTP website (Figure 4.10).

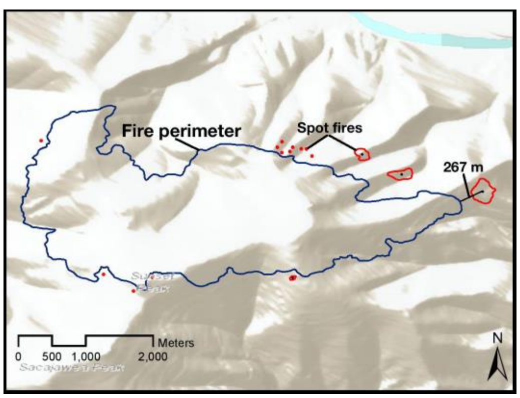


Figure 4.10 Location of the fire perimeter and spot fires for the Sheep Gap Fire located at the Lolo National Forest in Montana, USA, on 31 August 2017 at 2236 h local time.

All available NIROPS data captured during the 2017 fire season in the Northern Rockies region of the USA were downloaded from the National Interagency Fire Center (NIFC) FTP website and used for subsequent analysis. Spot fire identification and distance from the main fire perimeter were assessed by scripting an automated process. Specifically, for each fire and each consecutive day with IR data, the associated geo-spatial files were ordered by date and sequentially loaded to identify spot fires, calculate the size of the main fire area (m^2), the perimeter-to-area ratio (m^{-1}, fire perimeter shape), fire growth based on the percent increase in fire area since the previous time step, the size of each spot fire (m^2), the geographic location of its centroid, and the distance from each spot fire's centroid to the nearest main fire perimeter (m). Spot fires were defined as polygons less than 10 ha in size that were not connected to the main fire perimeter and isolated heat sources (points) that fell outside of the main fire area.

To assess the influence of important environmental factors on spotting distance, additional data related to each spot fire were collected. Hourly wind speeds ($m \cdot s^{-1}$) for the duration of each fire were estimated at 10 m height and 250 m resolution by using the Point Initialization feature and mass-conserving model within WindNinja [35]. The Point Initialization feature integrates observations from local weather stations to help drive the simulation and force the output to match the observations (within 0.1 $m \cdot s^{-1}$). The simulation domain was set to a 20 km × 20 km box centered on each fire, with all weather stations located within 5 km of the center and available via the MesoWest SynopticLabs API (available from https://synopticlabs.org/api/mesonet/[accessed 16 February2018]) used for Point Initialization. Vegetation-related data were retrieved from the LANDFIRE project for each fire (LF 1.4.0) [36]. Specifically, raster grids of canopy cover (%), canopy height (m × 10), and biophysical setting were compiled and resampled to 250 m resolution within the Northern Rockies region. Biophysical setting was used to classify cells as belonging to specific cover type groups to facilitate the utilization of Albini's [2] spot fire model. Terrain-related information, including slope position, elevation, and various metrics of terrain complexity, were compiled in 250 m raster grids for the Northern Rockies region. Specifically, slope position was calculated within a geographic information system (GIS) based on the topographic position index [37] and included six categories: Valley, Lower Slope, Flat Slope, Middle Slope, Upper Slope, and Ridge. For each fire perimeter, the mean and maximum elevations (m) that occurred within the main fire area were identified, as well as the standard deviation of elevation (m). For each spot fire, the distance from the lowest to highest elevation points (m) was identified within a circle having a 4 km radius centered at the spot fire location. The difference in elevation between the lowest and highest points (m) was also found within the same area.

4.3.2 Data analysis

The environmental data were used to capture specific information related to the spot fire with the maximum distance for each unique combination of fire and day, referred to as a fire-day. For each fire-day, the geographic location of the spot fire with the maximum distance was identified, and the data (i.e., wind speed, slope position, vegetation, etc.) from the grid cell nearest to the spot fire along the main fire perimeter were extracted. Figure 11 provides an example of the "raw" images used for the analysis. Additionally, the mean, maximum (continuous variables), and mode (categorical variables) values for each variable were calculated for the grid cells located immediately adjacent to the nearest cell and for all grid cells located within the main fire area. Prior to analysis, the dataset was modified to include only those fire-days that had a spot fire and spot fires for which the date of origin was known (i.e., the spot fires associated with the first day of each fire and spot fires associated with non-consecutive day IR flights were removed). Additionally, spot fires associated with fires where the mean canopy cover was less than 5% were removed to focus the analysis on spot fires originating from torching trees. To investigate the effects of the environmental variables on maximum spotting distance, linear mixed-effects regression analysis was performed in R using the lme4 and lmerTest packages [38,39]. The model parameters were estimated using maximum likelihood techniques, and the dependent variable (maximum spot fire distance) was transformed using the natural logarithm to address heteroscedasticity in the residuals.

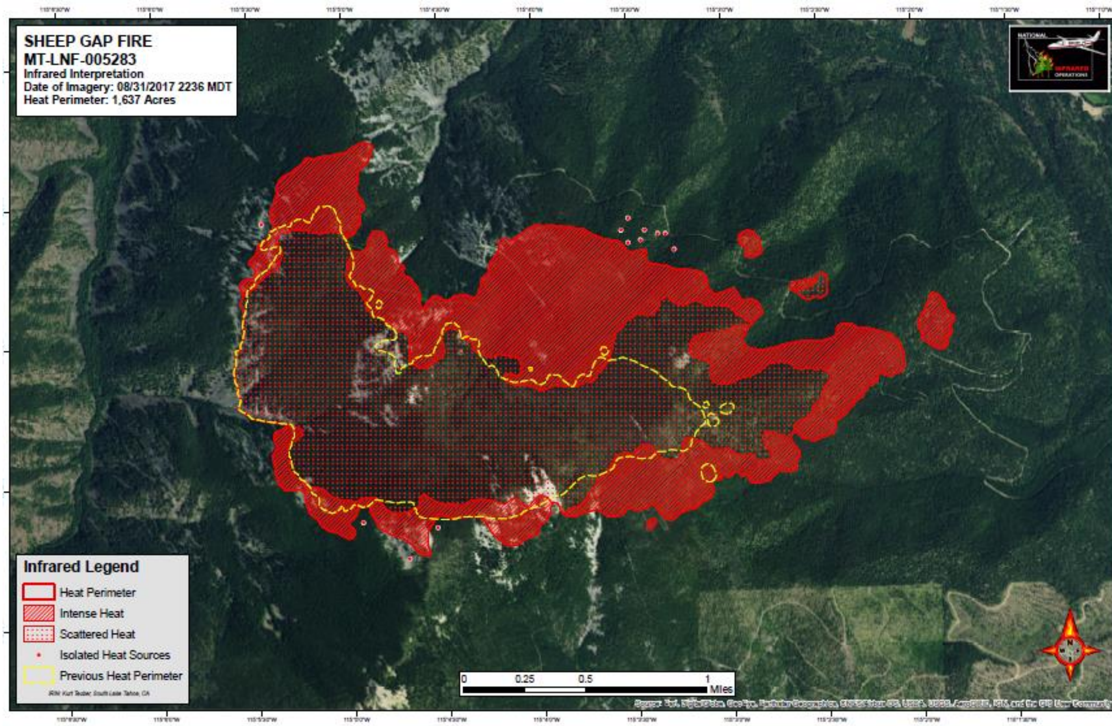


Figure 4.11 Original infrared maps corresponding to the information shown in Figure 4.10. Such information was used for analysis of transport distances of embers and the parameters that influence the distance.

Fire was treated as a random effect (random y intercepts), whereas the environmental variables were treated as fixed effects. The environmental variables and relevant interactions were included in the model, and a backward selection process was used to remove non-significant (p-value > 0.05) independent variables until a final model was obtained.

A comparison between the observed maximum spotting distance for each unique fire-day and the predicted theoretical maximum spot fire distance from Albini's [1] model was completed. To obtain predictions from Albini's (1979) model, a command line version (available fromhttps://github.com/firelab/behave [accessed 4 June 2018]) was used along with the inputs from the environmental variables previously described. Two wind speed scenarios were used based on whether the mean or maximum 24 h wind speed raster grids were utilized to extract the wind speed information. Additionally, the comparisons were made across a range of torching tree numbers, as it was not possible to gather or estimate this value from our dataset. The raw errors (predicted theoretical maximum distance – observed maximum distance) were calculated for each fire-day and then grouped by each wind speed and torching tree scenario to evaluate model performance. The proportion of fire-days in which the raw errors were positive (i.e., an over-prediction) was also calculated to assess performance.

5. Results and Discussion

5.1 Branch-scale studies

5.1.1 Dowel Factorial Study

The goal of a factorial study is to determine the relative importance of the independent variables on the response variable. In this study, the response is the time to generation. Figure 5.1 shows the mean square (sum of squares divided by degrees of freedom) of each statistically significant single-term effect (P _ 0.05). A logarithmic scale was used to allow all of the data to be visualized. The diameter of the dowels had the greatest sensitivity on the time to formation of embers. The mean square was nearly 2 orders of magnitude greater than any other parameter. On average, 2 mm diameter samples generated embers roughly 5x faster than 6 mm, with average ember generation times of 7.1 and 35.2 seconds, respectively (average generation time for all test cases are shown in Table A.C.2). These times to generation are similar to those that might be found in a wildland fire. During the tree-scale studies, 2.1-4.7 m tall trees were torched. On average, the trees torched for roughly 70 seconds. This suggests that the conditions the dowels experienced may be representative of conditions experienced during a wildland fire. The greater sensitivity of ember generation time to diameter is attributed to the smaller diameter dowels having a larger surface area to volume ratio. As a result, the relative mass loss rate due to oxidation is higher for the 2 mm cases, and the critical cross sectional area at which fracturing occurs is reached sooner.

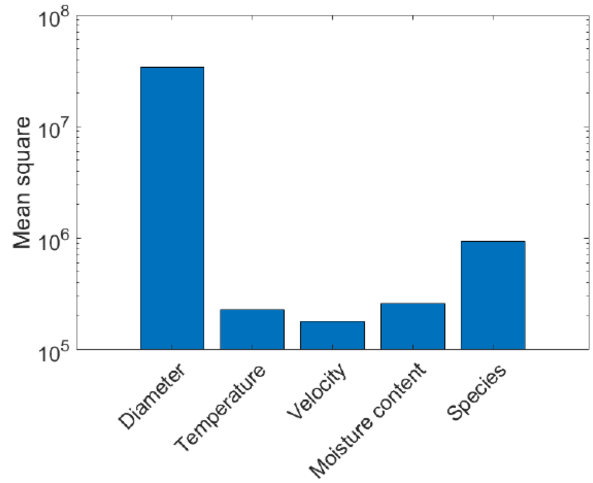


Figure 5.1 Mean square for main effects controlling ember generation.

The fuel species was the second most significant parameter influencing ember generation time. Of the four species evaluated, Douglas-fir and white oak had the largest difference in the average time to generation. Douglas-fir samples generated embers in roughly 64% of the time that white oak samples required (16.5 and 25.7 seconds, respectively). Crossflow temperature and velocity and fuel moisture content have little effect on the time to ember generation. The insignificance of temperature on time required for ember generation is attributed to both high and low temperature cases being above the pyrolysis and oxidation temperatures for

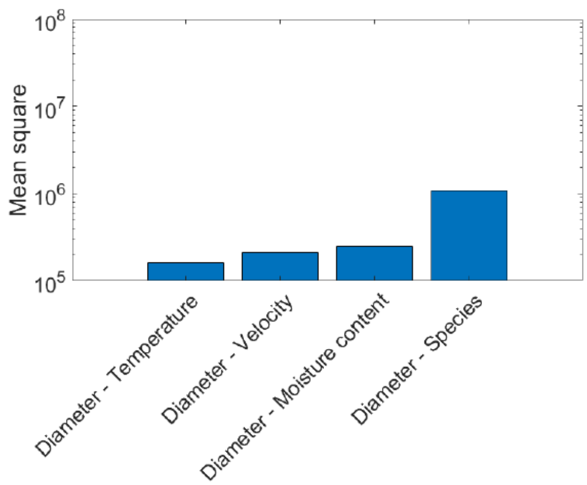


Figure 5.2 Mean square for couple interaction effects controlling ember generation.

the samples. Changes in the consumption of the fuel for the two temperatures (i.e., 1000 and 1200 K) had a secondary effect on generation time compared to other parameters. Crossflow velocity and moisture content both had weak effects on the time it takes to generate an ember. The observed sensitivities indicate that the fuel size has a greater influence on time to generation than environmental characteristics. More broadly, these results suggest that tree morphology, which controls the characteristic size of branches, may have the largest effect on the time to ember generation.

Figure 5.2 shows the mean square of each statistically significant interaction effect on time to ember generation. The diameter and species interaction had the largest influence on ember generation time, while the interaction between diameter and crossflow temperature had the weakest influence. The interaction between diameter and species can be thought of as the fuel morphology because the branch diameter distribution of a tree is dependent on its species. The observation that the interaction between diameter and species in the most important interaction term suggests that fuel morphology is critical to predicting the time required for ember generation.

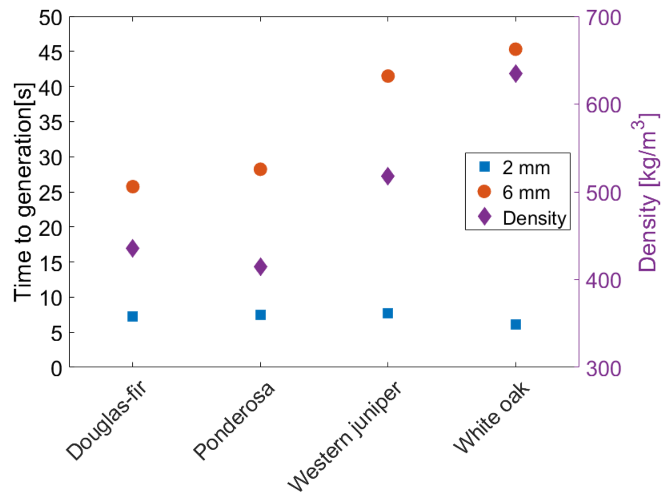


Figure 5.3 Average time to ember generation for all species tested.

Figure 5.3 shows the average time to generation for the species tested, along with the measured density of each species. Relatively little change is observed in time to generation between species for the 2 mm diameter samples, but a relatively large difference is observed for the 6 mm samples. The density of the fuels tended to be proportional to the time required for ember generation. Specifically, fuels with a higher density (e.g., white oak) tended to take longer to generate an ember.

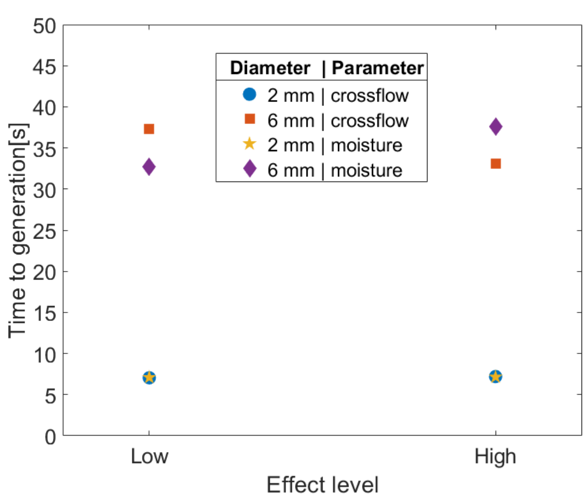


Figure 5.4 Interaction between moisture content (low: 0.5%, high: 15%), crossflow.

The coupled interactions between characteristic diameter and crossflow and moisture content are shown in Figure 5.4. The time to generation for the 6 mm diameter sample decreased at a lower moisture content. This is likely due to higher moisture content increasing the heat capacity of the sample, which increases the time required to reach pyrolysis and oxidation temperature [40]. Note that there is almost no change in generation time with a change in moisture content for the 2 mm samples. Previous research suggests that the moisture content of fine fuel (i.e., 2 mm diameter) is an important parameter for the spread of wildland fires [41]. The results from this study indicate that a minimum diameter exists below which moisture content does not influence time to ember generation for fine fuel, at least for the relatively small changes in moisture content used in this study. For the crossflow interactions, the average generation time was shorter for a high crossflow, 6 mm diameter sample than for the respective low crossflow case. This occurs because the drag-induced stress increases proportionally to the square of the crossflow velocity. A higher stress means the sample requires less time to be weakened (by pyrolysis and oxidation) before breakage. Similar to previous trends, there was almost no change in generation time between high and low crossflow velocities for the 2 mm diameter samples.

The observation that 2 mm diameter samples were unaffected by changes in species, crossflow velocity, moisture content, and crossflow temperature (not shown) suggests that as dowel diameter decreases there is a critical diameter (and resulting aspect ratio) where ember generation time becomes independent of other parameters tested (within the range evaluated in this study). This is attributed to the volume of the samples being small enough that changes in the pyrolysis and oxidation rates (due to changes in density, crossflow velocity, moisture content, and heat intensity) have relatively little effect on the time required for the fuel to be consumed and facilitate breaking.

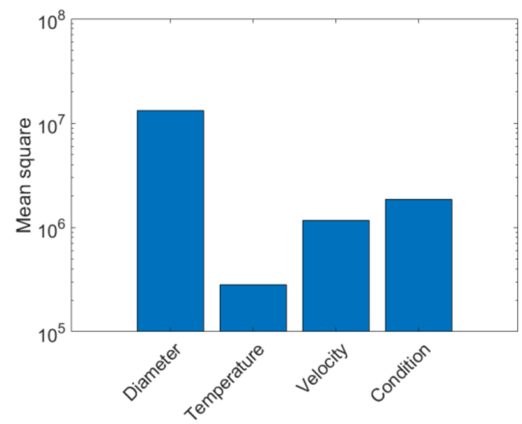


Figure 5.5 Mean square for main effects controlling ember generation when natural samples were evaluated. Condition refers to natural or dowel samples.

5.1.2 Evaluation of Natural Samples

A second factorial analysis was conducted to discern the effect that fuel condition (natural or dowel) has on the time to generation. The parameters varied were diameter, moisture content, crossflow temperature, crossflow velocity, and fuel condition. Douglas-fir samples were evaluated for this study. The mean square for each statistically significant single-term parameter is reported in Figure 5.5. The diameter of the sample had the greatest effect on time to generation. The second and third greatest sensitivities were the fuel condition (dowel or natural sample) and the crossflow velocity, respectively. The sensitivity to fuel condition indicates that the physical differences between dowels and natural samples do significantly affect time to ember generation. The mean squares of the diameter and crossflow velocity effects have relative magnitudes similar to those of the main factorial study (shown in Figure 5.1). Crossflow temperature had a small effect on the time required to generate an ember, similar to the results of the main factorial study. The moisture content was not a significant factor.

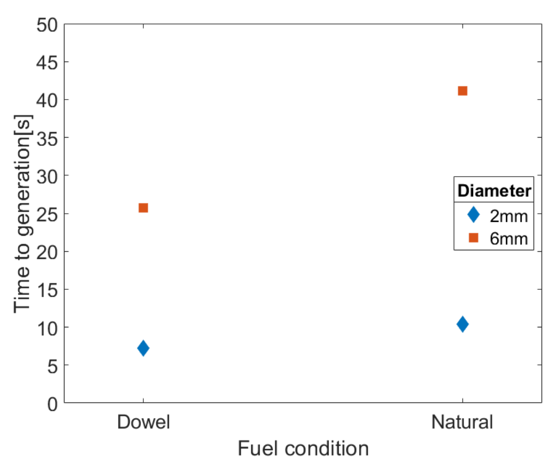


Figure 5.6 Interaction between fuel condition (natural and dowel) and diameter.

The three greatest interaction terms for the evaluation of natural samples were diameter coupled with crossflow velocity, diameter coupled with fuel condition, and crossflow velocity coupled with fuel condition. The diameter and crossflow velocity coupling was evaluated in Figure 5.4, and is not repeated here. Figure 5.6 shows the interaction between fuel condition and diameter. The natural samples take longer to generate an ember for both 2 and 6 mm diameter samples (43% and 60% increase for 2 and 6 mm samples, respectively).

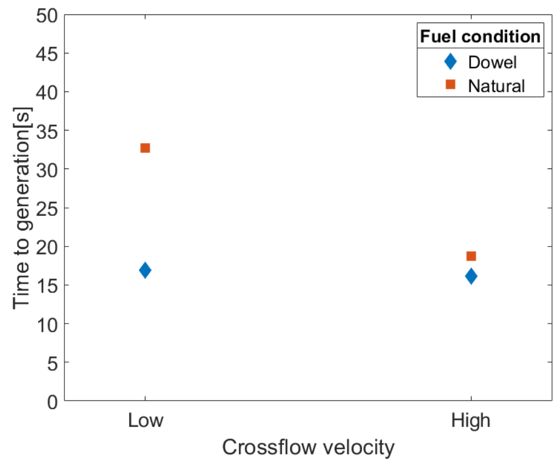


Figure 5.7 Interaction between crossflow velocity and fuel condition (natural and dowel).

Figure 5.7 shows the interaction between crossflow velocity and fuel condition. Crossflow velocity does not have a significant effect on time to generation for the dowel samples (as discussed previously), but it is a significant effect for the natural samples. This is attributed to natural dowels having defects which cause significantly more drag at higher crossflow velocities.

5.2 Tree-scale studies

Figure 5.8a shows the average ember flux as a function of distance from to the closest tree (i.e., location 1 in Figure 4.6). All references to distance are with respect to this location. The peak ember flux was roughly 1500 embers/m^2 at 1.5 m for the western juniper and grand fir trees. At the same location, ponderosa pine had the smallest number flux of embers (roughly 550 embers m^{-2}). A quadratic-like decay in ember flux as the distance increases is observed for all species. This sensitivity is expected because the area where an ember can land increases as the square of radius. The relative difference in ember flux between species stays constant as the distance from the closest tree increases. At 1.5 m from the tree, ponderosa pine generates roughly 1/3 as much of an ember flux as grand fir (548 and 1478 embers/m^2, respectively). Similarly, when the distance is increased to 7.6 m, ponderosa pine generates approximately 1/3 of the ember flux as grand fir.

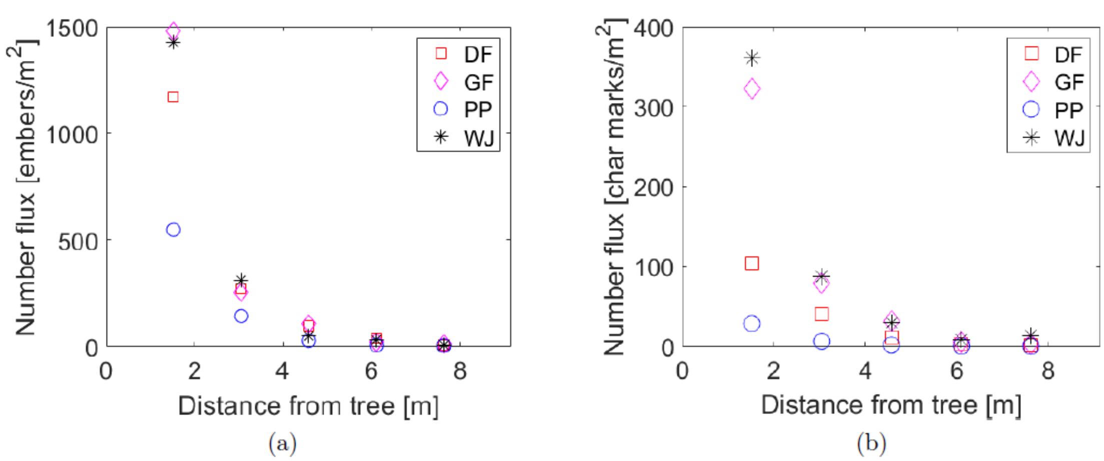


Figure 5.8 Average ember flux (panel a) and char mark flux (panel b) with respect to distance from the closest tree.

Figure 5.8b shows the average char mark flux per test relative to the distance from the closest tree. The reader is reminded that "ember" refers to material collected in the trays filled with water, while "char mark" refers to the black marks left on the fire resistant fabric by hot embers. The peak char mark flux was roughly 375 char marks/m2 at 1.5 m from the tree (for western juniper). This number flux is roughly 25% of the highest number flux for embers, showing that the majority of the embers generated are not hot enough to char the fabric. The smallest number flux of char marks was for ponderosa pine (i.e., 30 char marks m^{-2}). A quadratic-like decay in the char mark flux, similar to Figure 5.8a, is also observed. It is noted that the relative difference in char mark flux between species decreases only marginally as the distance from the tree(s) increases. Ponderosa pine produced approximately 10% as much char mark flux as western juniper at a distance of 1.5 m from the closest tree (29 and 361 char marks m^{-2}, respectively). At 7.6 m from the tree, ponderosa pine generated roughly 5% as much char mark flux as western juniper (0.4 and 14 char marks m^{-2}). These observations show a species dependence in the number of embers and char marks, and in the ratio of char marks to total number of embers.

Figure 5.9 shows a boxplot of the ember flux per kilogram of mass loss (specific ember flux) and char mark flux per kilogram of mass loss (specific char mark flux) for each test. Each "box-and-whiskers" represents three data points (i.e., the three replicates for each set of testing conditions). Generally, the specific ember flux decreases when the number of trees increases. The highest median value of specific ember flux when only one tree was burned was roughly 180 embers/m^2-kg (for Douglas-fir). In contrast, the highest median value of specific ember flux was 27 embers/m^2-kg when five trees were burned (for ponderosa pine). It is also observed that the range of specific ember fluxes decreases as the number of trees increases. When only one tree was burned (including all species of trees), the specific ember flux varies from roughly 10-325 embers/m^2-kg. However, the specific ember fluxes vary from 0-35 embers/m^2-kg when five trees were burned. This reduction in specific ember flux is attributed to embers generated from tree(s) upwind being consumed by the fire from downwind trees before they are able to be deposited. It should also be noted that there is less difference in specific ember flux between species when five trees are burned. When one tree is burned, western juniper has the lowest median specific ember flux (57 embers/m^2-kg), which is 30% of the highest median specific ember flux (Douglas-fir, 181 embers/ m^2-kg). In contrast for tests with five trees, the lowest median specific ember flux is only 20% of the highest median specific ember flux (5 embers/ m^2-kg for grand fir and 27 embers/ m^2-kg for ponderosa pine). This observation suggests that for large fires (assuming the same mass is lost for each species of tree) the species of

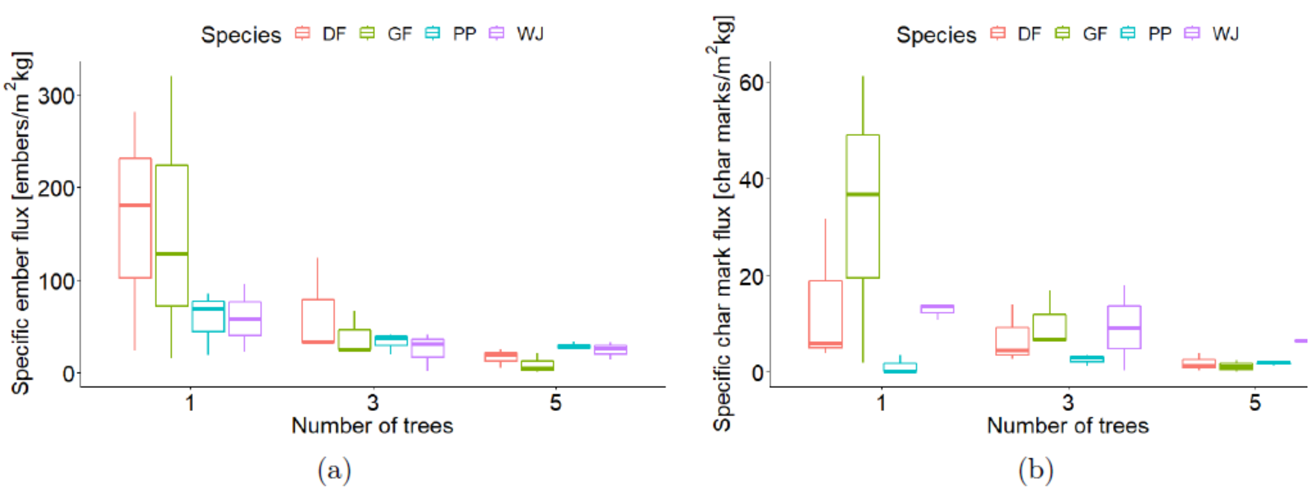


Figure 5.9 Specific ember flux (4a) and specific char mark flux (4b) with respect to number of trees per test.

trees does not have as much effect on the specific ember flux as when only a few trees are burned. More research, with more trees burned per test and different spacing of trees, are needed to determine any limits for the specific ember flux generated with respect to the number of trees.

It is observed that on average, the specific char mark flux decreases when the number of trees increases (shown in Figure 5.9b), similar to the specific ember flux. For example, the median char mark flux for grand fir decreases from 37 char marks/m^2-kg for one tree to 1 char mark/m^2-kg for five trees. In contrast, ponderosa pine has almost no change in specific char mark flux when the number of trees increases (median specific char mark flux of 0.5 char marks/m^2-kg for one tree and 2 char marks/m^2-kg for five trees).

The average specific ember flux and average specific char mark flux for all tests is plotted for each species of tree in Figure 5.10. This information can be used to help scale results to trees of different heights and fuel loading if fuel consumption rates are known or can be estimated. Note that each data point is the average from all tests for a given species of tree. On average, Douglas-fir generated the highest average specific ember flux, while western juniper generated the lowest (81 and 36 embers/ m^{2}kg, respectively). Western juniper generated a similar ember flux to Douglas-fir and grand fir (see Figure 5.8a), which indicates that its lower specific ember flux is due to western juniper trees losing more mass than other species. When considering "hot" embers, grand fir and western juniper generated the highest specific char mark flux, with average specific char mark fluxes of 15 and 10 char marks/ m^{2}kg, respectively. Ponderosa pine generated approximately 2 char marks per square meter per kilogram of mass loss, which is the fewest of the species tested. Figure 5.10 also shows the average ratio of char marks to embers for each species. Western juniper has the largest char/ember ratio of roughly 32%, indicating that on average, western juniper generated the highest fraction of "hot" embers. Ponderosa pine generated the lowest fraction of "hot" embers, with only roughly 6% of the total ponderosa pine embers collected being hot enough to leave char marks. The results shown in Figure 5.10 are noteworthy because they show that the fuel species affects the specific ember flux and specific char mark flux.

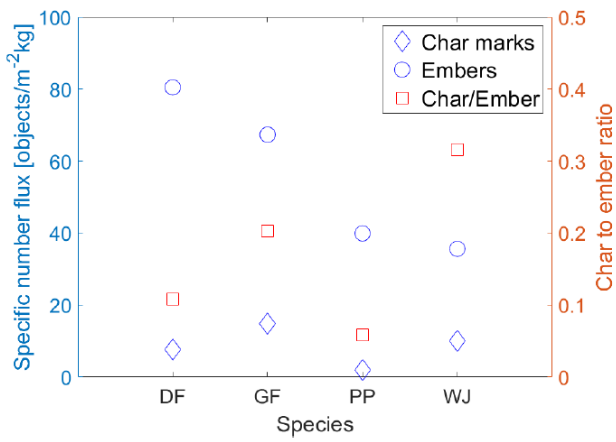


Figure 5.10 Total number of embers and char marks generated per kilogram of mass loss with respect to species.

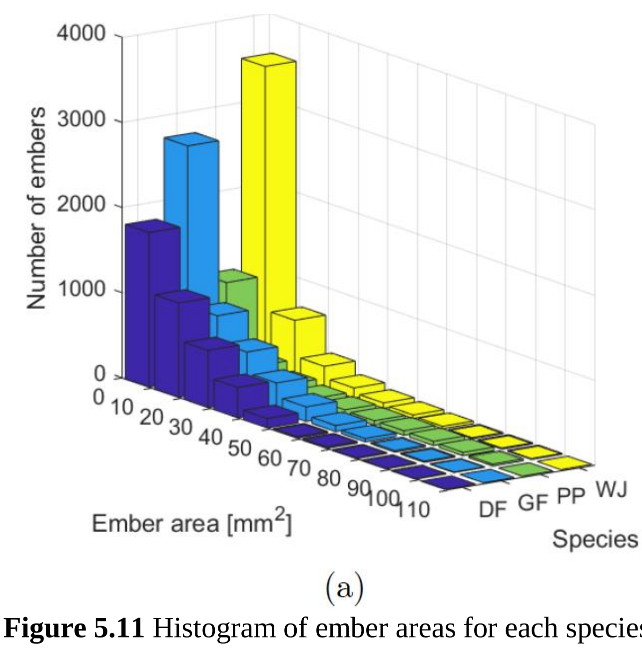
Table 5.1 Average and 90th percentiles of ember and char mark areas for all species evaluated.

Species	Average ember area [mm^2]	Ember area 90th percentile [mm^2]	Average char mark area [mm^2]	Char area 90th percentile [mm^2]
Douglas-fir	15	33	56	87
Grand fir	15	34	50	108
Ponderosa pine	33	87	11	33
Western Juniper	10	23	64	138

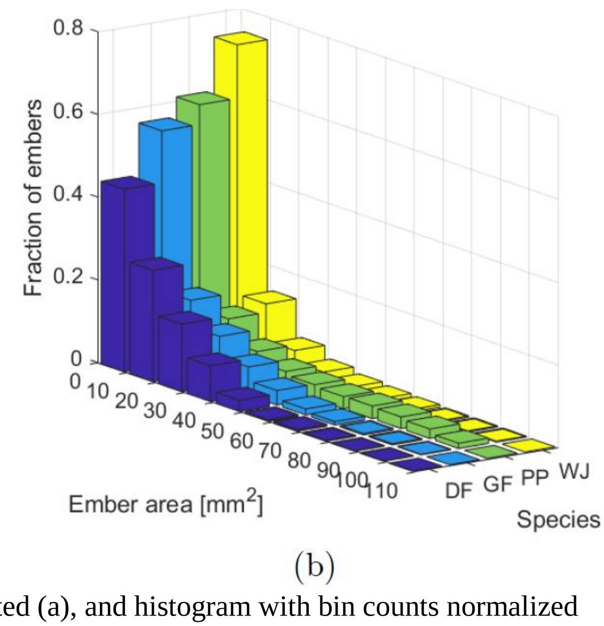
The average ember and char mark areas for each species are shown in Table 5.1. For all species, except ponderosa pine, the average and 90th percentile char mark areas are larger than the respective ember areas. This is attributed to heat spreading across the fabric, thus charring a region larger than the cross-section of each ember. Western juniper has the largest average char mark area, despite having the smallest average ember area. This observation is attributed to the qualitative observation that ash remained on the surface of the char marks for western juniper tests. In contrast, charred or partially charred embers remained on the fabric for the other species. The observation of ash suggests a larger heat release from western juniper embers than embers from the other species, and thus more energy transferred to the fabric. The average char mark area for ponderosa pine was roughly 11 mm^2, which is smaller than the average area of embers generated by ponderosa pine. This observation, along with the low char mark flux to ember flux ratio for ponderosa pine, may indicate that ponderosa pine embers (needles in this study) cool more rapidly during transport than other species.

It is noted that previous work that used fire resistant fabric to collect embers observed that 90% of char marks had an area less than 10 mm^2 [24]. In contrast, the 90th percentile char mark areas in this study vary from 33 to 138 mm^2, depending on species (see Table 5.1). It is plausible that the larger size of char marks in this study results from the relatively close proximity of the fabric to the location where the embers were generated. The embers from the prior study traveled farther (i.e., between 10.5 and 11.7 m), and thus had more time to burn before deposition. There may also be physical or chemical differences in the fabric used in this and the previous study that affect the amount of energy required to leave a char mark.

A histogram of ember areas is shown in Figure 5.11a and can be used to compare ember cross-sectional areas to previous work. The majority of embers, irrespective of the species of tree, were 0-10 mm^2 in area. However, the size distribution of embers differs significantly between species. To compare size distributions, the fraction of embers in each ember area "bin" is shown in Figure 5.11b. It is noted that western juniper embers had the narrowest distribution of areas, with roughly 90% of embers being less than 23 mm^2 in area. The smaller size of embers from western juniper is attributed to the small size of western juniper scales [42]. Ponderosa pine embers have the largest variation in



(a)



(b)

Figure 5.11 Histogram of ember areas for each species tested (a), and histogram with bin counts normalized by species (b).

area, with 90% of embers having an area of less than 87 mm^2. Ponderosa pine generated the largest embers, with an average area of 33 mm^2. Generally, the ember areas for this study are smaller than previous work. Manzello, Maranghides, and Mell [43] collected embers with an average area of 120 and 212 mm^2 generated from Douglas-fir trees with 2.4 and 4.5 m crown heights, respectively. The cause for the smaller ember areas in this study requires further investigation, but may be caused by differences in the experimental arrangement (e.g., method of tree ignition and size of filter used to screen embers from the water).

A regression model was created to help identify the most significant physical parameters influencing ember generation and the formation of char marks, within the scope of variables evaluated in this study. The linear regression model for ember flux per kilogram of mass loss

(EFM, units of embers/ m^2-kg) is:

$$\begin{aligned} EFM^{1/3} &= \beta_0 + \beta_1 MC + \beta_2 H + \beta_3 H * MC + \beta_4 H * PML + \delta_1 H * NT_3 \\ &+ \delta_2 H * NT_5 + \delta_3 GF * MC + \delta_4 PP * MC + \delta_5 WJ * MC \end{aligned} \quad (1)$$

where MC is the average moisture content per test, H is the average tree height per test, NT is the number of trees as a categorical variable, PML is the mass loss as a percent of the initial mass, GF is the categorical variable for grand fir, PP is the categorical variable for ponderosa pine, and WJ is the categorical variable for western juniper. Note that the response variable (EFM) was transformed by taking the cube root. The base cases for species and number of trees are Douglas-fir and one tree. This model was selected using the glmulti package in R, which finds the best model based on the Akaike information criteria corrected for small sample size.

Table 5.2 Estimates of coefficients and their significance for linear regression of ember flux per kilogram of mass loss (Equation 2). The significance codes are: *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1.

Term	Estimate	
$\hat{\beta}_0$ (intercept)	-7.86418	*
$\hat{\beta}_1$ (MC)	45.07387	***
$\hat{\beta}_2$ (H)	4.01948	***
$\hat{\beta}_3$ (H*MC)	-11.62040	***
$\hat{\beta}_4$ (H*PML)	-2.59574	***
$\hat{\delta}_1$ (H*NT_3)	-0.10504	
$\hat{\delta}_2$ (H*NT_5)	-0.37406	***
$\hat{\delta}_3$ (MC*GF)	-1.17994	
$\hat{\delta}_4$ (MC*PP)	-4.37484	*
$\hat{\delta}_5$ (MC*WJ)	-4.32631	*
$R^2_{adjusted}$	0.6626	***

The estimates of the coefficients (β terms) and their relative significance are shown in Table 5.2. The moisture content has a significant effect on the specific ember flux for all species except grand fir (terms β_1, δ_4, and δ_5). The positive value for β_1 indicates that increasing the moisture content for Douglas-fir trees increases the specific ember flux, while the negative values for δ_4 and δ_5 indicates that increasing the moisture content for ponderosa pine and western juniper decreases the specific ember flux. The exact cause for this difference is not clear. However, it is plausible that for some species increased moisture content reduces the number of embers generated by suppressing the fire intensity. In contrast, for other species of tree (e.g., Douglas-fir and grand fir), increasing the moisture content may lead to a higher number of embers generated because of ruptures in the structure of the fuel as water evaporates and boils.

The average tree height per test has a significant coupled interaction with average moisture content, percent mass loss, and the number of trees. Looking at the interaction of height and number of trees (β_2 and δ_2), it is noted that for tests with one tree (β_2) the specific ember flux increases with an increase in the average tree height. However, the specific ember flux decreases with an increase in average tree height for tests with five trees (δ_2). Presumably reduction in embers with more trees occurs because embers generated from trees upwind are either consumed by the fire from downwind trees or are deposited on the downwind trees.

A regression model was created for the specific char mark flux per test, similar to the specific ember flux model, in an effort to identify key parameters that influence the generation of embers that can form char marks. The best linear regression model for the specific char flux (CFM, units of char marks/m^2-kg) was:

$$\begin{aligned} CFM^{1/2} &= \beta_0 + \beta_1 MC + \beta_2 EFM + \beta_3 MC * EFM \\ &+ \delta_1 GF * EFM + \delta_2 PP * EFM + \delta_3 WJ * EFM \end{aligned} \tag{2}$$

where MC is the average moisture content per test. Species of tree was treated as a categorical factor with the base case of Douglas-fir, so the β_2 term can be interpreted to be the interaction between Douglas-fir and specific ember flux. Note that the response variable (CFM) was transformed by taking the square root. This model was selected based on Akaike information criteria corrected for a sample size using the glmulti package in R.

Several observations are evident about the sensitivity of specific char mark flux to changes in moisture content and ember flux per mass loss based on _ values. These values are shown in Table 5.3. The first observation is that the EFM terms (β_2; δ_1; δ_2; δ_3) for each species are statistically significant. This means that the specific char mark flux is dependent on the specific ember flux for each species, as expected. A second observation is that the coefficient estimate for δ_2 has a negative sign. This indicates that as the specific ember flux for ponderosa pine increases, the specific char mark flux decreases, which is in contrast to all other species. Douglas-fir, grand fir, and western juniper all experience an increase in specific char mark flux when specific ember flux is increased. This observation is attributed to the tree morphology and how embers were released.

The observations gained from the linear regression model are potentially significant because they indicate that studies quantifying ember fluxes provide representative results for char mark fluxes (i.e., potential ignition sources), albeit the ratio of char marks to embers is species dependent. Although the moisture content appears in this model, it is not statistically significant. This suggests that the moisture content does not affect the portion of embers generated that are hot enough energy to leave char marks.

Table 5.3 Estimates of coefficients and their significance for linear regression of specific char mark flux (Equation 3). The significance codes are: *** < 0.001 < ** < 0.01 < * < 0.05 <. < 0.1.

Term	Estimate	
$\hat{\beta}_0$ (intercept)	-1.18243	.
$\hat{\beta}_1$ (Avg_MC)	1.2184	
$\hat{\beta}_2$ EFM	0.9076	***
$\hat{\beta}_3$ Avg_MC*EFM	-0.16496	
$\hat{\delta}_1$ GF*EFM	0.36393	***
$\hat{\delta}_2$ PP*EFM	-0.35861	**
$\hat{\delta}_3$ WJ*EFM	0.32374	**
$R^2_{adjusted}$	0.8526	***

5.3 Forest-scale studies

5.3.1 Spot fire distance

The compiled dataset from the Northern Rockies for the 2017 fire season contained 7214 unique spot fires that occurred on 48 fires over the course of 447 unique fire-day combinations. Approximately 94% of all spot fires had distances that were ≤ 500 m from the main fire perimeter, with a maximum verified distance of 2.7 km (Figure 5.12). The distribution of spot fire distances obtained in this study is similar (in terms of the shape and range of values) to other distributions produced using theoretical models [44,45]. In several simulation scenarios, both Wang [44] and Koo et al. [45] characterized the majority (>50%)

of firebrands as landing less than 300–350 m from their source, depending on various modeling assumptions such as burnout time, firebrand shape, and initial mass.

The maximum spotting distances for each unique fire-day had mean and median values of 436 m and 355 m, respectively. Additionally, there were 31 unique fire-days in which the maximum recorded distance exceeded 1 km. The farthest verified distance of 2.7 km occurred sometime on 6 September during the Monahan Fire in the Flathead National Forest in northwestern Montana. These maximum distances are similar to distances observed on other large fires that have occurred in the Northern Rocky Mountains, including a 2–3 km distance witnessed on 8 August 1936 during the Galatea fire in the Canadian Rockies [46], a 1 km distance between 29 and 30 August 1967 during the Sundance Fire in northern Idaho [47] and a 1–2 km distance during the 2003 fire season in British Columbia [48]. However, in this dataset, we did not record the extreme distances that have also been observed such as the 16–19 km distances seen during a 26 km fire run over 9 h on 1 September 1967 during the Sundance Fire (Anderson 1968).

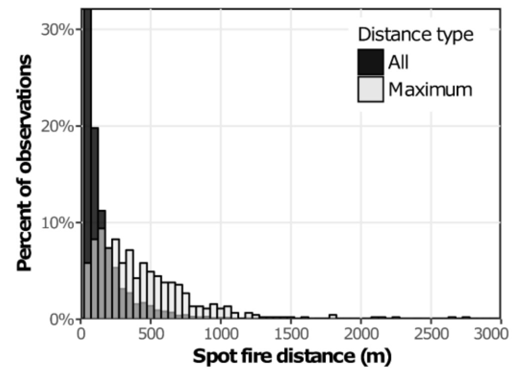


Figure 5.12 Distribution of spot fire distances for all spots fires assembled in the dataset (All) and for spot fires with the maximum distance for each unique fire-day combination (Maximum).

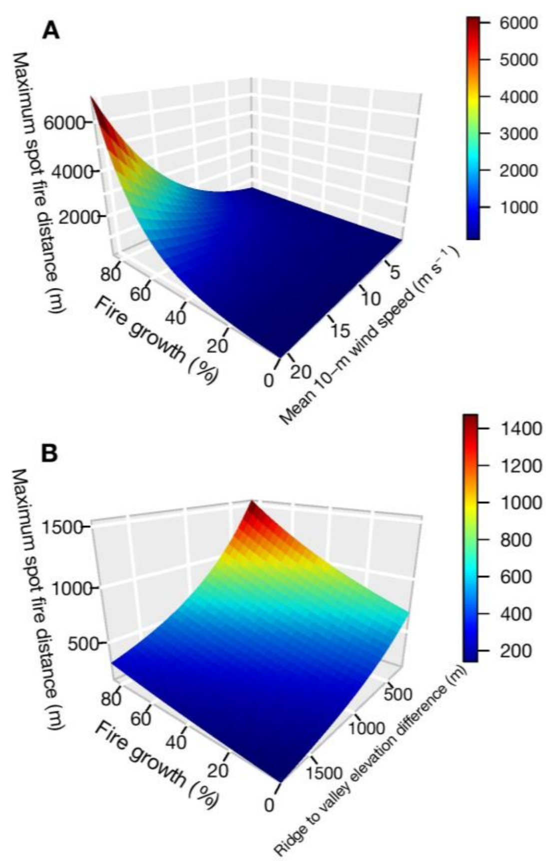


Figure 5.13 Predicted maximum spot fire distance across increasing fire growth and mean 10 m wind speed (A) and increasing fire growth and ridge-to-valley elevation distance (B).

The linear mixed-effects analysis of maximum spotting distance produced a model that identified several significant relationships with the environment-, vegetation-, and fire-related variables and explained approximately 13% and 38% of the total variability based on the fixed effects alone and both the fixed and random effects, respectively. A significant positive correlation was identified between the maximum spot fire distance and an interaction between the maximum 10 m wind speed recorded within the main fire perimeter and fire growth. According to the proposed statistical model, fires that grew substantially compared with the previous day (>50% increase in growth) and had relatively high wind speeds (>10 $m \cdot s^{-1}$) had the potential to produce spot fire distances in excess of 1 km (Figure 5.13). The importance of wind speed on potential spotting distance is well known [49,50], but the dependence on fire growth suggests that other conditions associated with large fire growth (e.g., convection column development) are needed for long-range spotting to occur. This finding is in line with several theoretical [1,51–53] and experimental [54] analyses that emphasize the importance of characteristics of the convection column, heat release rate, or lofting height in their estimation of potential spotting distance.

5.3.2 Comparison with Albini's (1979) model

The comparisons of the observed maximum spotting distances with the predictions from Albini's [1] model indicated that the proportion of fire-days with an over-prediction (i.e., raw error > 0) varied primarily according to the wind speed scenario used to run the model (Figure 5.14). When the 24 h mean wind speed grids were utilized, Albini's [1] model had a tendency to produce maximum spotting distances that were less than observed, with fewer than 45% of the fire-days having an over-prediction, which resulted in a mean under-prediction of approximately 186 m across the range of torching tree numbers considered. However, when the 24 h maximum wind speeds grids were utilized, the majority of fire-days had an over-prediction, the mean of which was approximately 149 m. Given the unknowns in regards to the static and dynamic factors (both local and broad scale) that influence spotting distance, it is difficult to determine the reasons for the observed under-predictions produced by Albini's model [1]. Low-quality and inappropriate inputs such as inaccurate wind speed information or the failure of Albini's model to incorporate additional important factors may have contributed to some of the under-prediction bias. The results of this analysis suggest that, in terms of operational application, it is important to utilize the high end of wind speed forecasts or model simulation results when making predictions with Albini's model [1]. This will increase the likelihood that Albini's (1979) model provides an overestimate of maximum spotting distance, which, in terms of operational application, is more desirable than an underestimate.

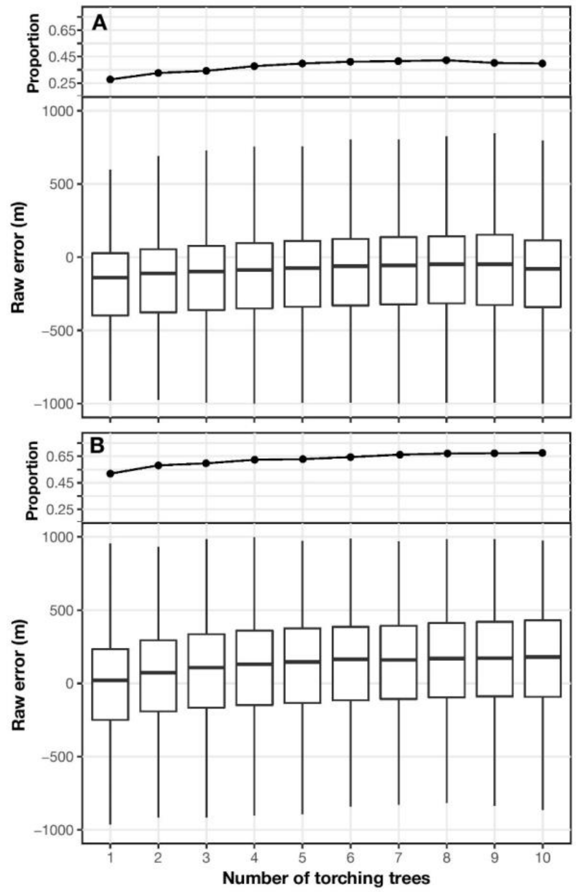


Figure 5.14 Boxplots of the raw error (Albini's [1] model prediction –observed maximum spot fire distance) for each unique fire-day across an increasing number of torching trees based on using the 24 h mean wind speed values (A) and the 24 h maximum wind speed values (B).

6. Conclusions and Implications for Management and Future Research

6.1 Summary and Conclusions

In the branch-scale study, the effects of diameter (i.e. aspect ratio), species, moisture content, fuel condition, crossflow temperature, and crossflow velocity on time required for ember generation were evaluated at branch-scales. Visual images of the samples burning in a wind tunnel were used to determine the time required to generate embers. These times were used in a factorial study to identify which of the parameters evaluated in this work were most influential on the time to generate embers.

The specific conclusions from the branch-scale study are as follows for the range of conditions evaluated:

1. The diameter of a sample has the greatest effect on the time to ember generation. As a result, it was expected that tree morphology has a significant effect on ember generation because it influences the diameter and aspect ratio of branches.
2. Bark can have a significant effect on the time required to generate an ember. Natural samples of Douglas-fir generated embers roughly 55% slower than dowels.
3. The time required for 2 mm samples to generate embers is relatively insensitive to moisture content, species, and crossflow velocity and is only weakly affected by fuel condition. This conclusion suggests that there exists a critical diameter below which ember generation time is nearly independent of other parameters.

In the tree-scale study, embers and char marks from a series of tests involving the torching of Douglas fir, grand fir, ponderosa pine, and western juniper trees were collected. Groups of trees (1, 3, or 5) were arranged in a bed of straw. Embers were collected in sets of trays filled with water and fire resistant fabric located downwind. A total of 27 trees were burned for each species of tree. "Hot" embers were identified from char marks left on fire resistant fabric, while the total number and sizes of embers were determined from samples collected in water trays.

The specific conclusions for the tree-scale study are as follows:

1. The number of embers and char marks generated per kilogram of mass loss varies significantly between species of trees. Although Douglas-fir trees generate the highest ember flux per kilogram of mass loss, they do not generate the highest char mark flux (i.e., "hot" embers) per kilogram of mass loss. Grand firs generate the highest char mark flux per kilogram of mass loss, with roughly 15 char marks/m^2-kg. Ponderosa pine generates the lowest char mark flux per mass loss (2 char marks/m^2-kg).
2. In general, only a fraction of the total embers collected were hot enough to leave char marks, and this fraction varied between species. It was observed that western juniper had the highest average percentage of "hot" embers with approximately 30% of the total embers being hot enough to leave char marks, in contrast to just 5% for Ponderosa pine.
3. The parameters that significantly affect the ember flux generated per mass loss are not identical to the parameters that significantly affect the char mark flux generated per mass loss. The three most significant parameters that affect ember flux per mass loss are the number of trees burned, percent mass loss, and species of tree. The char mark flux per mass loss is dependent on the ember flux per mass loss and the average moisture content of the trees burned.

Across both the tree and branch-scales, the fuel morphology was shown to significantly affect the ember generation process. At the branch-scale, the species and diameter (i.e., fuel morphology) were shown to be the two parameters that had the greatest effect on the time required for an ember to generate. At the tree-scale, the fuel species was the parameter that had the most significant effect on the number of embers and char marks generated. Each species has a different fuel loading and needle/branch characteristics. This supports the branch-scale observation that the diameter plays a significant role in the ember generation process.

With respect to full-scale studies on prescribed or naturally occurring wild fires the research found it very difficult to characterize ember production and transport given the many uncertainties associated with the process of placing collectors and analyzing the source of the embers they contained. The more promising method of scaling laboratory data to the field scale was through the method of using infrared imagery of fire occurrence and analyzing for maximum ember transport. While still fraught with much uncertainty, this method provides a quantitative assessment of model accuracy.

6.2 Implications for Management

Spotting during wildland fires (i.e., ember generation, lofting, transport, and ignition) remains a critical but difficult to predict phenomena. It directly affects fire manager's ability to successfully conduct prescribed fires and it greatly increases both the difficulty of suppressing wildfires and the hazard posed to wildland firefighters engaged in suppression operations. Ultimately, providing fire managers with an enhanced capacity to predict the potential locations and timing of spot fires would improve their ability to make safe and effective decisions. In an effort to move closer to that ultimate goal, this study has provided fire managers with additional practical information that can be used either directly when making fire behavior predictions or indirectly, to improve and inform existing fire behavior models.

Specifically, the implications of the project results are:

1. The species-specific ember and char fluxes produced by this work can be used to enhance/inform existing and future fire behavior models. That is, physically-based fire behavior models that attempt to incorporate the physics of wildland fire spread could use the findings produced here to better understand local scale ember generation that can then be fed into the models to better estimate ember lofting height and transport distance.
2. Operational fire behavior modelers that utilize the existing suite of empirical and semi-empirical fire behavior models now have additional information about the performance of a widely used theoretical model of maximum spotting distance. It is apparent from the work presented here that although it is generally accepted that Albini's model [2] over-predicts the maximum spotting distance that is typically observed on wildland fires, we have seen that in some cases the model may actually under-predict the maximum spotting distance. In order to avoid this, it is important that fire modelers use a high estimate of potential wind speed from weather forecasts or simulated weather/wind model outputs in order to avoid this outcome.

6.3 Limitations and Future Research

Spotting is a simple term for a very complex process that incorporates thermal decomposition of biomass and lofting and transport of burning embers in the fire plume as well as ultimate reignition of unburning vegetation some distance from the original fire. The ember production process, or from the modeling perspective the ember source term, has proven elusive to fire scientists. While this work and likely that of other JFSP funded projects has pushed the knowledge boundary further, additional understanding is needed. The methods developed in this work to use infrared imagery of fire perimeters to estimate maximum spotting distances is novel and should be extended to additional fuel types, and burning conditions. Other studies that are using infrared imagery at the individual tree scale as well as the methods developed here are providing new understanding of species specific ember production. Future research efforts should continue to extend successful methods to new burning conditions, fuels, and identify source terms (i.e., embers/kg fuel consumed). It is only with long term continued focus can successful knowledge development occur.

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8. Appendices

Appendix A: Contact Information for Key Project Personnel

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Appendix B: List of Completed/Planned Publications

1) Paige, W., Wagenbrenner, N., Butler, B., Blunck, D., "An analysis of spotting distances during the 2017 fire season in the Northern Rockies, USA." *Canadian Journal of Forestry Research*, vol. 49, 317-325 (2019).

2) Hudson, T., Blunck, D., "Effects of fuel characteristics on ember generation," *International Journal of Wildland Fire,"* (accepted).

3) Hudson, T., Paige, W., Butler, B., "Effects of fuel morphology on ember generation at the tree-scale," *in preparation for International Journal of Wildland Fire.*

4) Hudson, T., Multi-scale study of ember production and transport under multiple environmental and fuel conditions, M.S. Thesis, Oregon State University, 2018.

Appendix C: Metadata

The videos, images, and other data collected will be made available on the US Forest Service website. The documents listed below include the metadata for the tree- and branch-scale aspects of the generation study.

<u>Metadata Document for Tree-scale Ember Generation</u>

IDENTIFICATION INFORMATION

Citation for Data Publication

Originator (authors): Tyler Hudson and David Blunck
Title: Tree-scale Ember Generation Study
Data Presentation Form: Digital (.tif files)
Publication Place: Corvallis, OR, United States of America
Publisher: *Oregon State University, School of Mechanical, Industrial and Manufacturing Eng.*

Description of Data Publication:
Abstract (summary of data): This data was collected as part of a project funded by the Joint Fire Science Program (Grant 15-1-04-9). The objective of the project was to identify what physical conditions have the greatest influence on the generation of embers (also known as firebrands). The efforts consisted of experiments at both laboratory (i.e., branch-scale) and outdoor (i.e., tree-scale) studies. This document describes the data collected for the latter study. Details of the experimental approach can be found in Tyler Hudson's thesis, "Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions," 2018, Oregon State University.

Description of files:

- The folder "Ember images" contains labeled images of all the embers collected during testing. The notation is "##-##"", where the first number indicates the test and the second indicates the tray location.
- The folder "Fabric images" contains labeled images of all the fabric with char marks. The images have the same naming convention as the "Ember images" folder.
- B-lab burns information.xlsx contains all the testing conditions.
- The folder "Archive IR data" contains all the IR videos taken of the tests. These have not been processed.
- The folder "Videos" contains videos of most of the tests. A couple tests are missing videos due to technical difficulties.

MATLAB files:

- Char_area_calculator.m determines the area of each char mark/ember from the .tiff images.
- Fabric_Collection_Analysis_removed_duplicates.m performs all other calculations and plotting. The code is broken up into sections, so the whole thing does not need to (nor is it recommended to) run at once. Load the workspace (workspace 050619.mat) to load saved variables for plotting.
- Tray_Collection_Analysis_vs.m is obsolete, but was used to perform calculations for the ember images.
- R files: Regression Model.R performs the linear regression analysis using the data contained in per_test_results.csv

Purpose (why data were collected): The data was collected in an effort to identify which factors have the greatest influence on generation behavior of firebrand at tree-scales.

Status:

Progress: Complete

Maintenance and Update Frequency: None planned

Description of Geographic Extent (description of where data was collected): Experiments were performed at 4228 NW Springhill Drive, Albany, OR, United States of America.

Theme Keywords

Author's choice Keywords: firebrands, embers,

ISO19115 Keywords: environment

R&D Taxonomic Keywords: Fire and Wildland/urban interface, Fire suppression

Place Keywords (include state(s) if applicable): Albany, Oregon, United States of America

Use Constraints: None

Point of Contact (for data)

Organization: Oregon State University

Contact Person: David L. Blunck

Contact Position: Associate Professor

Contact Address: 204 Rogers Hall, Corvallis, OR 97331

Contact Voice Telephone: 541-737-7095

Data Set Credit (who funded this work?): Joint Fire Science Program

Cross-references (citations for publications that USED the data we are archiving, or related data sets)

Complete Citation: A paper is currently under review for International Journal of Wildland Fire with Hudson, T., Paige, W., Butler, B., Blunck, D as authors. The expected title will be Effects of Fuel Morphology on Ember Generation Characteristics at the Tree-scale.

DATA QUALITY INFORMATION

Attribute Accuracy

Attribute Accuracy Report (assessment of how "true" attributes values are): uncertainty analysis was reported in the publication under review to provide estimates of the true values

Completeness Report (info about omissions, selection criteria): the information provided is believed to be complete with the exception of some of the videos of the burns. Some were not available because of technical difficulties.

Lineage-methodology (information about steps in field or laboratory work, can be repeated)

Methodology Keywords: tree burns, ember generation, outdoor

Methodology Description: Trees of varying species, sizes, and moisture content, and numbers of tree (1, 3 or 5) were burned. The embers that were generated were allowed to land in trays of water and on fabric treated with a fire retardant. The embers collected in trays gave indication about the number of embers that were released whereas the fabric charred only when hot embers landed. The goal was to identify which parameters (e.g., species, number of tree, etc.) have the largest influence on generation characteristics. Complete details of the methodology can be found in the thesis: Tyler Hudson, “Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions,” Oregon State University, 2018.

Methodology Citation

Complete Citation: Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions,” Oregon State University, 2018.

Online Linkage: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/1n79h969p?fbclid=IwAR1jKbgThapT-rCZ8L5w2yQjnj5xdI02XVSooWBZl10XEzlOTAWI6ZyPlwA

Lineage-Process Steps (steps followed after data collection)

Process description: The embers collected in water trays were allowed to dry and were then spread on pieces of paper. Pictures of the paper with the embers were then collected and analyzed to determine the number and size of the embers. Similarly, images were collected of the fabric with char marks which in turn were processed to determine the number and size of char marks.

ENTITY AND ATTRIBUTE INFORMATION

Overview description of variables in each data set:

Species of trees (Douglas-fir, Grand fir, ponderosa pine, juniper)
Moisture content
Initial mass of trees
Number of trees (1, 3 and 5)
Corrected initial mass
Final mass
Corrected final mass
Mass Loss
Height of tree
DBH
Mass of Straw (used to start torching of trees)
Depth of Straw (used to start torching of trees)
Wind information

Citation for publication containing data summary: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/1n79h969p?fbclid=IwAR1jKbgThapT-rCZ8L5w2yQjnj5xdI02XVSooWBZl10XEzlOTAWI6ZyPlwA

DISTRIBUTION INFORMATION

- The folder "Ember images" contains labeled images of all the embers collected during testing. The notation is "##-##"", where the first number indicates the test and the second indicates the tray location.
- The folder "Fabric images" contains labeled images of all the fabric with char marks. The images have the same naming convention as the "Ember images" folder.
- B-lab burns information.xlsx contains all the testing conditions.

- The folder "Archive IR data" contains all the IR videos taken of the tests. These have not been processed.
- The folder "Videos" contains videos of most of the tests. A couple tests are missing videos due to technical difficulties.

MATLAB files:

- Char_area_calculator.m determines the area of each char mark/ember from the .tiff images.
- Fabric_Collection_Analysis_removed_duplicates.m performs all other calculations and plotting. The code is broken up into sections, so the whole thing does not need to (nor is it recommended to) run at once. Load the workspace (workspace 050619.mat) to load saved variables for plotting.
- Tray_Collection_Analysis_vs.m is obsolete, but was used to perform calculations for the ember images.
- R files: Regression Model.R performs the linear regression analysis using the data contained in per_test_results.csv

METADATA REFERENCE INFORMATION

Contact Person: Tyler Hudson
Contact Address: tyler.robert.hudson@gmail.com
Contact Telephone: 720-339-8083

Metadata Document for Branch-scale Ember Generation

IDENTIFICATION INFORMATION

Citation for Data Publication

Originator (authors): Tyler Hudson and David Blunck
Title: Branch-scale Ember Generation Study
Data Presentation Form: Digital (.mov files)
Publication Place: Corvallis, OR, United States of America
Publisher: *Oregon State University, School of Mechanical, Industrial and Manufacturing Eng.*

Description of Data Publication:

Abstract (summary of data): This data was collected as part of a project funded by the Joint Fire Science Program (Grant 15-1-04-9). The objective of the project was to identify what physical conditions have the greatest influence on the generation of embers (also known as firebrands). The efforts consisted of experiments at both laboratory (i.e., branch-scale) and outdoor (i.e., tree-scale) studies. This document describes the data collected for the former study. Details of the experimental approach can be found in Tyler Hudson's thesis, "Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions," 2018, Oregon State University.

Description of files:

- Time_to_generation.xlsx is a spreadsheet containing the time to generation for each video as well as the experimental conditions for each video. The time to generation was determined by recording the frame
number where the ember(s) was/were generated.
- Screening Study Data.xlsx contains all the testing conditions and notes for each test.
- The matlab scripts (pretty_plots_r_outputs.m and natural_vs_squares_results.m) plot the results from the Factorial Analysis.
- The Factorial Analysis R script uses the 3 replicate data.csv and Natural vs dowel data.csv to complete the factorial analysis.
- Video data is in folder "Screening Study Videos".

Contact: Tyler Hudson
Email: tyler.robert.hudson@gmail.com

Purpose (why data were collected): The data was collected in an effort to identify which factors have the greatest influence on generation behavior of firebrand at branch-scales.

Status:

Progress: Complete
Maintenance and Update Frequency: None planned
Description of Geographic Extent (description of where data was collected): Experiments were performed at the Aero Engineering Laboratory (AEL) at Oregon State University in Corvallis, OR, United States of America.

Theme Keywords
Author's choice Keywords: firebrands, embers,

ISO19115 Keywords: environment
R&D Taxonomic Keywords: Fire and Wildland/urban interface, Fire suppression
Place Keywords (include state(s) if applicable: Oregon, United States of America

Use Constraints: None

Point of Contact (for data)

Organization: Oregon State University
Contact Person: David L. Blunck
Contact Position: Associate Professor
Contact Address: 204 Rogers Hall, Corvallis, OR 97331
Contact Voice Telephone: 541-737-7095

Data Set Credit (who funded this work?): Joint Fire Science Program

Cross-references (citations for publications that USED the data we are archiving, or related data sets)

Complete Citation: Hudson, T., Blunck, D., Effects of fuel characteristics on ember generation characteristics at branch-scales, *International Journal of Wildland Fire*, 2019, 28, 941-950.

Online Linkage: https://www.publish.csiro.au/WF/pdf/WF19075

DATA QUALITY INFORMATION

Attribute Accuracy

Attribute Accuracy Report (assessment of how "true" attributes values are): uncertainty analysis was reported in the publication listed above to provide estimates of the true values

Completeness Report (info about omissions, selection criteria): the information provided is believed to be complete

Lineage-methodology (information about steps in field or laboratory work, can be repeated)

Methodology Keywords: wind tunnel, ember generation

Methodology Description: Dowels or pieces of natural samples (i.e., twigs) were inserted into a vertical wind tunnel with flames. The time from inserting the samples into the tunnel until the time that the samples broke (i.e., formed embers) was measured using videos. The characteristics of the wind speed, temperature, diameter of the dowels, the species of wood, moisture content, or natural vs processes samples was systematically varied. The goal was to identify which parameters have the largest influence on generation characteristics. Complete details of the methodology can be found in the thesis: Tyler Hudson, "Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions," Oregon State University, 2018.

Methodology Citation

Complete Citation: Multi-scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions," Oregon State University, 2018.

Online Linkage: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/1n79h969p?fbclid=IwAR1jKbgThapT-rCZ8L5w2yQjnj5xdI02XVSooWBZl10XEzlOTAWI6ZyPlwA

Lineage-Process Steps (steps followed after data collection)

Process description: The time from inserting the samples into the tunnel until the time that the samples broke (i.e., formed embers) was measured using videos. The time to generation was statistically analyzed relative to the parameters (e.g., diameter of the samples) that were varied to identify most significant parameters.

ENTITY AND ATTRIBUTE INFORMATION

Overview description of variables in each data set:

Name: Operator of experiment
Date of experiment
Data filename
Diameter of the sample
Natural sample (e.g., twig) or dowel
Species of tree (Douglas-fir, white oak, juniper, ponderosa pine)
Heat (i.e., temperature of the wind tunnel)
Cross-flow (velocity)
Moisture content of the sample

P1 –P3 and Propane temp were used to determine the flow rates of the fuel. These values were used to control the heat variable

Citation for publication containing data summary: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/1n79h969p?fbclid=IwAR1jKbgThapT-rCZ8L5w2yQjnj5xdI02XVSooWBZl10XEzlOTAWI6ZyPlwA

DISTRIBUTION INFORMATION

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